Hydrol. Earth Syst. Sci. Discuss., 10, 7161–7196, 2013
www.hydrol-earth-syst-sci-discuss.net/10/7161/2013/
doi:10.5194/hessd-10-7161-2013

Hydrology and Earth System Sciences
Open Access
Discussions

A new method to measure bowen ratios using high resolution vertical dry and wet bulb temperature profiles

T. Euser[1], W. Luxemburg[1], C. Everson[2], M. Mengistu[2], A. Clulow[2], and W. Bastiaanssen[1]

[1]Delft University of Technology, Water Resources Section, Stevinweg 1, 2628 CN Delft, the Netherlands
[2]University of KwaZulu-Natal, School of Agricultural, Earth and Environmental Sciences, Private Bag X01, Scottsville, Pietermaritzburg, 3209, South Africa

Received: 2 May 2013 – Accepted: 24 May 2013 – Published: 5 June 2013

Correspondence to: T. Euser (t.euser@tudelft.nl)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The Bowen ratio surface energy balance method is a relatively simple method to determine the latent heat flux and the actual land surface evaporation. Despite its simplicity, the Bowen ratio method is generally considered to be unreliable due to the use of two-level sensors that are installed by default in operational Bowen ratio systems. In this paper we present the concept of a new measurement methodology to estimate the Bowen ratio from high resolution vertical dry and wet bulb temperature profiles. A short field experiment with Distributed Temperature Sensing (DTS) in a fibre optic cable having 13 levels was undertaken. A dry and a wetted section of a fibre optic cable were suspended on a 6 m high tower installed over a sugar beet trial near Pietermaritzburg (South Africa). Using the DTS cable as a psychrometer, a near continuous observation of vapour pressure and temperature at 0.20 m intervals was established. These data allows the computation of the Bowen ratio with a high precision. By linking the Bowen ratio to net radiation and soil heat flux, the daytime latent heat flux was estimated. The latent heat flux derived from DTS-based Bowen ratio (BR-DTS) showed consistent agreement (correlation coefficients between 0.97 and 0.98) with results derived from eddy covariance, surface layer scintillometer and surface renewal techniques. The latent heat from BR-DTS overestimated the latent heat derived with the eddy covariance by 4 % and the latent heat derived with the surface layer scintillometer by 8 %. Through this research, a new window is opened to engage on simplified, inexpensive and easy to interpret in situ measurement techniques for measuring evaporation.

1 Introduction

Evaporation is – after rainfall – the most important term of the hydrological water balance. Evaporation is also a major term of the land surface energy balance, i.e. the latent heat flux. Knowledge on the consumptive use of water is key for water scarce areas, and consumptive use exists mainly of evaporation (Perry, 2007). An accurate estimation of the actual evaporation can among others be used for hydrological studies, environmental studies, irrigation studies, climate change studies, water accounting studies and solving international conflicts on the verification of water use. It is often difficult and costly to estimate the actual evaporation above land surfaces in an accurate and affordable manner. Therefore, actual evaporation is often estimated using numerical simulation of hydrological processes (e.g. Schoups et al., 2008; Uhlenbrook et al., 2004), Soil-Vegetation-Atmosphere-Transfer processes (e.g. Sellers et al., 1986; Wipfler et al., 2011) and remote sensing algorithms (e.g. Bastiaanssen et al., 2012; Courault et al., 2005; Kalma et al., 2008). Models, however, often require ground measurements for calibration (Xing et al., 2008). Winsemius et al. (2008) demonstrated that calibration of hydrological models can also be achieved with spatially distributed evaporation data.

There are simple and more advanced techniques available for in situ measurements of evaporation, each with a different theory, degree of complexity, a certain budget for operationalising the system and expertise to interpret the raw data. Review papers on lysimeters, soil water balances, the Bowen ratio method, eddy co-variances, scintillometers and surface renewal techniques are provided by Burt et al. (2005); Dugas et al. (1991); Malek and Bingham (1993); Mauder et al. (2013); Rana and Katerjib (2000); Teixeira and Bastiaanssen (2010), among others. There is a large difference in accuracy between the various methodologies. By absence of a standard technology, it remains necessary to continue the research and development on new solutions to find simple and affordable methodologies to measure evaporation under actual field conditions. The current paper is an example of that, and wishes to prove that in concept the measurement method described can yield results comparable to conventional methods, and can even be a valuable addition or improvement to existing methods.

The conventional Bowen ratio surface energy balance methodology (BR) is a relatively simple technique that integrates net available energy with the ratio of the sensible and latent heat flux (Bowen, 1926). Combination of the Bowen ratio with net radiation (R_n) and soil heat flux (G) makes it feasible to determine latent heat fluxes. Examples of

BR can be found in for instance Aston (1985); Black and McNaughton (2012); Jara et al. (1998); Peacock and Hess (2004); Savage et al. (2009b) and Teixeira et al. (2007). The BR method is often derived from two level air temperature and water vapour pressure sensors. Using two levels generates a major drawback of the BR methodology: the determination of BR is not free from errors related to sensor inaccuracies (e.g. Angus and Watts, 1984; Fritschen and Qian, 1990; Fuchs and Tanner, 1970).

A disadvantage of the BR method is that there is a sensitivity to the biases of two separate sensors which measure gradients of air temperature and vapour pressure (Perez et al., 1999; Savage et al., 1997). In addition, there is the possibility of discontinuous data when the Bowen ratio approaches -1, as this leads to infinity for the available energy during post processing of the results (Savage et al., 2009b), but this is a minor aspect.

In this paper we present an alternative method to measure the Bowen ratio with a strongly improved accuracy referred to as the BR-DTS method. This method determines the temperature and vapour pressure gradients using a Distributed Temperature Sensing (DTS) methodology. With the DTS technique (Selker et al., 2006; Tyler et al., 2009) temperature measurements with a high temporal and spatial resolution are obtained using one sensor, a fibre optic cable. Vertical high resolution air temperature and vapour pressure profiles are obtained with a spatial resolution of 0.2 m across a total height of 4.5 m. This eliminates the major shortcoming of the conventional BR method with separate sensors on 2 levels. The DTS technique is more and more applied in different research fields, showing the potential of the technique (Hoes et al., 2009; Krzeminska et al., 2011; Steele-Dunne et al., 2010; Westhoff et al., 2010).

The aim of this study was to verify whether the concept of the BR-DTS method can be used to estimate an accurate Bowen ratio number. A limited period has been selected to undertake a first investigation. The results are compared with conventional in situ measurement techniques. The advantages and disadvantages of this new BR-DTS technique are discussed.

2 Study area

The field measurements with the BR-DTS technology were performed on a sugar beet trial field located at the Ukulinga research farm of the University of KwaZulu-Natal, Pietermaritzburg (South Africa). This field was used by the University of KwaZulu-Natal for an experiment with bio fuels. The field is located at 40°40′22″ S, and 30°24′25″ E and the land has a gentle slope (< 5 %) (see Fig. 1). The size of the site is $80 \times 80\,m^2$ and the elevation is 780 m a.m.s.l. The crop height of the sugar beet during the experiment was about 0.5 m and the crops were irrigated with drip irrigation once a week.

The BR-DTS system (Fig. 1) was installed on a lattice mast orientated so that the longest fetch corresponded to the dominant wind direction, which is from southeast. This site was selected because of an on-going micro-meteorological field experiment of the University of KwaZulu-Natal in the same field. Measurements were conducted from 9 November 2011 (00:00 LT) to 18 November 2011 (14:00 LT). Due to power supply failures, the data collection between 11 and 14 November are incomplete.

The latent heat flux estimated from the BR-DTS system were compared with the flux results from three conventional techniques. The conventional measurements are referred to as eddy covariance (EC), surface layer scintillometer (SLS) and surface renewal (SR). The advantage of the scintillometer method, is that it is able to measure the area-integrated sensible heat flux across a transect, thereby representing a better field average value of the sensible heat flux (e.g. Meijninger and de Bruin, 2000).

HESSD
10, 7161–7196, 2013

3 Materials and methods

3.1 BR-DTS method

3.1.1 Theory

The BR method relies on several assumptions (Angus and Watts, 1984; Fritschen and Simpson, 1989; Gavilán and Berengena, 2007; Spittlehouse and Black, 1980). One basic assumption is that the fluxes are one-dimensional only, with no horizontal gradients, and that measurement sensors are located within the equilibrium sub-layer, where fluxes are constant with height (e.g. Dyer and Hicks, 1970). It is further assumed that the land surface exists of a homogeneous surface with respect to sources and sinks of heat, water vapour and momentum. The turbulent exchange coefficients for heat and water vapour are assumed to be identical, hence equal surface roughness lengths for heat and water vapour, and identical correction functions for buoyancy (Todd et al., 2000). Under these prevailing conditions, the Bowen ratio can be determined from differences of actual air temperature (ΔT_a) and actual vapour pressure (Δe_a) over a vertical air column (Bowen, 1926):

$$\beta = \frac{H}{\mathrm{LE}} = \gamma \frac{\Delta T_a}{\Delta e_a} \quad (1)$$

where γ is the psychrometric constant. For an elevation of 780 m a.m.s.l., the constant is 0.059 kPa °C^{-1} (Maidment, 1993). The actual vapour pressure can be determined from dry and wet bulb measurements applying the principle of a psychrometer (Allen et al., 1998). The equation for actual vapour pressure reads as:

$$e_a = e_s - \gamma (T_a - T_w) \quad (2)$$

where, T_w is the temperature of a wetted and vented surface (e.g. sphere), often referred to as the wet bulb temperature (°C), e_s the saturated vapour pressure (kPa), and

HESSD
10, 7161–7196, 2013

e_a is the actual vapour pressure (kPa). The saturated vapour pressure e_s follows from T_w as (Allen et al., 1998):

$$e_s = 0.61\, e^{\frac{17.3\, T_w}{237 + T_w}}. \tag{3}$$

Combination of Eqs. (1) and (2) and application to a vertical air column, with observations at two heights referred to in the subscripts, after re-expression yields:

$$\beta = \gamma \frac{T_{a,2} - T_{a,1}}{\left(e_{s,2} - e_{s,1}\right) - \gamma \left(T_{a,2} - T_{a,1}\right) + \gamma \left(T_{w,2} - T_{w,1}\right)}. \tag{4}$$

Or in general:

$$\beta = \gamma \frac{\Delta T_a}{\Delta e_s - \gamma \Delta T_a + \gamma \Delta T_w}. \tag{5}$$

Equation (5) shows that the gradient of air temperature is the key for an accurate determination of the Bowen ratio, and that the absolute values are less important. Therefore, the differences between multiple sensors should be warranted. This remark does not hold true for Δe_s, because the saturation vapour pressure is in the formula of Eq. (5) derived from the wet bulb temperatures, and the relation between the wet bulb temperature and corresponding saturation vapour pressure (Eq. 3) is strongly non-linear. The consequence of this non-linearity is that, when for two points the wet bulb temperatures are equally off and hence the gradient ΔT_w remains the same, the gradient Δe_s can still be erroneous. Hence, the observed wet bulb temperature must approximate the real wet bulb temperature. By having the vertical gradients from multiple levels, the Bowen ratio can be determined far more accurate than for the situation where separate sensors on 2 levels are involved.

HESSD
10, 7161–7196, 2013

After inclusion of knowledge on the H/LE flux ratio in the energy balance equation, the latent and sensible heat flux (Eqs. 6 and 7) can be calculated directly (e.g. Aston, 1985; Fritschen, 1965; Perez et al., 1999):

$$\mathrm{LE} = \frac{R_\mathrm{n} - G}{1 + \beta} \tag{6}$$

$$H = \frac{\beta\,(R_\mathrm{n} - G)}{1 + \beta} \tag{7}$$

where LE is the latent heat flux ($\mathrm{Wm^{-2}}$), R_n is the net radiation ($\mathrm{Wm^{-2}}$), H is the sensible heat flux ($\mathrm{Wm^{-2}}$), and G is the soil heat flux ($\mathrm{Wm^{-2}}$).

3.1.2 DTS experimental set-up

The temperature distribution along a fibre optic cable is measured with the Distributed Temperature Sensing (DTS) technique. The DTS measurement device consists of two main elements: (1) a computer equipped with a laser transmitter and receiver and (2) a fibre optic cable. The computer transmits short laser pulses and receives the reflected frequencies. One of these reflected frequencies has a temperature dependent amplitude (Selker et al., 2006). From the travel time of laser light in the fibre optic cable, the origin (i.e. position along the cable) of the reflected signal can be deduced as well as the corresponding temperature. The observed temperature is an average over a cable segment. The segment length, and therefore the spatial resolution, depends on the interval time of the laser pulse. For this field campaign the ORYX laser pulse of Sensornet was used with a spatial resolution of 1 m along the cable (Sen, 2009). For the measurements a data collection time of 5 min was used resulting in an accuracy higher than 0.05 °C (Sen, 2009). For the sake of comparison with the other flux measurement devices, Bowen ratio values from BR-DTS values were averaged over 30 min. More background information on the DTS technology can be found in Selker et al. (2006) and Tyler et al. (2009).

HESSD
10, 7161–7196, 2013

The temperature measurements along the cable are subjected to a calibration process (Selker et al., 2006). To perform an on-line calibration process, two segments of the cable with a certain distance apart were placed in the same water-filled calibration tank for the total duration of the measuring period. The temperature of the water in the tank was measured continuously and the slope and offset coefficients for the calibration were determined every 5 min.

For the BR-DTS system, two parts of the same fibre optic cable were suspended from a 6 m high lattice mast. These parts of the cable were spiralled to obtain a vertical resolution of 0.2 m of temperature observation along the axis of the spiral. One of the spirals was dry and the other was kept wet with a cotton wrap around the cable. The dry and wet bulb temperatures in the air column were obtained from the dry and wet cables respectively. Water was supplied continuously to the wet cable at two locations (at the top of the spiral and half way) (see Fig. 2).

The largest part of the 235 m of cable, used for this field campaign, ran over the ground from the computer to the lattice mast. A distance of 15 m of cable was permanently placed in the calibration tank, ahead of the 30 m spiralled cable that ran from the bottom to the top of the mast. From there the DTS cable went down comprising the next 30 m wrapped and wetted cable. The last 15 m of the cable remained in the same calibration tank. To determine the exact position of the bottom of each spiralled cable, parts of the cable at the bottom were temporary immersed into an ice bath. The bottom line of this experimental set up is that the BR-DTS tower was 6 m tall and that dry bulb and wet bulb temperatures were measured with a vertical interval of 0.2 m from the ground surface to a height of 5.25 m.

3.1.3 Processing of data

The temperatures of the dry spiral were used to determine the gradients for air temperature (ΔT_a, °C). Although a white cable was used, the temperature of the dry spiralled cable might deviate from the actual air temperature due to exposure to direct sunlight.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

HESSD
10, 7161–7196, 2013

Bowen ratio with DTS

T. Euser et al.

This is acceptable for a Bowen ratio as long as the gradients do not deviate from reality (see Sect. 3.1.1).

The wet bulb temperature is derived from the wetted cable. In order to conclude how well the actual wet bulb temperature is measured under these specific circumstances, we have conducted tests in a separate laboratory set-up after the field experiment. In the laboratory set-up we continuously wetted a 1 m cotton cloth from the top. We observed the temperature of the water when applied at the top and the temperature of the water when dripping down the cloth at three locations. With a fan we artificially created air circulation, measured wind speeds and also air temperature. Applying the psychrometer theory on these measurements and comparing it with the actual humidity in the laboratory provides an indication at which point of the cable the actual wet bulb temperature is achieved. The laboratory set-up showed that the amount of water supplied is crucial and at least some wind is required. Evidently, sufficient water is required to establish evaporation to achieve a wet bulb temperature. However, too much supply of water lengthens the adjustment distance. In our laboratory test set-up, we found an adjustment distance of approximately 0.5–1.0 m. In the laboratory the air temperature and relative humidity were constantly kept at 20 °C and 70 % respectively. The water supplied in the laboratory had a temperature of 5 °C higher than the wet bulb temperature. We determined that in the laboratory a minimum wind speed of 1 ms^{-1} was required to obtain the wet bulb temperature that is in equilibrium with the surrounding environment.

Examining the temperature observations of the spiralled wet cable in the field clearly indicated the locations where water was released for permanent saturation of the cotton (Fig. 3). In Fig. 3 all sections are indicated that were excluded for the gradient analysis. Ideally the measuring points would be located on a logarithmic profile. A logarithmic profile (dotted line in Fig. 3) is fitted on two points on which the influence of the support or water supplying system is assumed to be limited (red circles in Fig. 3). Comparison with the logarithmic profiles shows that certain observation points fit very well, while others show a large deviation. There are different reasons for exclusion of data points.

HESSD
10, 7161–7196, 2013

The top 0.75 m was influenced by the supporting installation and the bottom 1 m was strongly influenced by the canopy of the sugar beet crop, and therefore, did not measure the temperatures above the crop. Points in the middle section (2.4–3.4 m) and at the top (4.6–5.25 m) are excluded due to the water supply. This can be explained by the distance needed for the temperature of the wet cotton to become in equilibrium with the ambient conditions. The adjustment distance for the field experiment appeared to be longer than expected on the basis of the laboratory test, this can be explained by warmer water that was supplied to the cotton in the field experiment. In addition, more water was supplied as compared to the laboratory set up. Larger amounts of water were required for the sake of wetting the entire cable segment. Based on this we excluded 1 m of the middle section (5 data points) and 0.65 m at the top (3 data points). A total of 13 data levels in the vertical profile were used to determine the Bowen ratio.

The Bowen ratio for BR-DTS and the corresponding correlation coefficient were determined through a linear regression between the dry cable temperature and vapour pressure, every 30 min for the same 13 data points (Fig. 4). The advantage of using 13 data points instead of two is that more stable Bowen ratio values can be obtained.

3.2 Reference techniques

BR-DTS, eddy covariance (EC), surface layer scintillometer (SLS) and surface renewal (SR) measurements took place coincidently. These techniques all measured the sensible heat flux (H). In addition, the EC equipment also measured directly the latent heat flux (LE). Therefore, we distinguish between EC-direct (LE_{EC}) and EC-indirect (LE_{SEB}).

As the frequency of measurement for all the aforementioned techniques was different, all data were converted to 30 min intervals for comparison.

3.2.1 Eddy covariance (EC)

Two different eddy covariance systems, a Campbell Scientific EC150 system and an Applied Technologies sonic anemometer had been installed to obtain fluxes of water vapour, carbon dioxide, and sensible heat above the sugar beet canopy. Both systems were mounted on a lattice mast at 2.0 and 1.5 m above the ground surface, respectively. The EC150 system consisted of a CR3000 datalogger, a CSAT3 three-dimensional sonic anemometer (Campbell Scientific Inc., Logan, Utah, USA), an EC150 open path gas analyser and a HMP45C temperature and humidity probe. The Applied Technologies system was used to obtain H from the sonic temperature and LE from the shortened energy balance equation with ancillary measurements of R_n and G (Sect. 3.3).

3.2.2 Surface layer scintillometer (SLS)

A dual-beam surface layer scintillometer (Scintec model SLS40-A) was used to measure the sensible heat flux density every 2 min. The scintillometer's transmitter and receiver were positioned at a height of 1.5 m above the soil surface (thus 0.5 m above the canopy) and the path length between the receiver and transmitter units was 90 m. The SLS operates at a wavelength of 670 nm. The SLS40-A employs a diode laser source with an output wavelength of 670 nm and 1 mW (2 mW peak) mean output power. The beam displacement and detector separation distances are 2.5 mm each with a detector diameter of 2.7 mm. Measurements are obtained with a frequency of 1 kHz and subsequent several micrometeorological parameters are calculated, among others the sensible heat flux H.

3.2.3 Surface renewal (SR)

For the surface renewal method, one unshielded type-E fine-wire thermocouple (75 µm diameter) was used to measure air temperature fluctuations. It was placed at a height of 1.0 m above the soil surface. Thermocouple measurement was done differentially and air temperature data was sampled at a frequency of 10 Hz. Time lags of 0.40 and 0.80 s were used for the surface renewal analysis before forming the second, third and fifth order of air temperature structure function values as required by the Atta (1977) approach. Data were averaged every two minutes.

HESSD
10, 7161–7196, 2013

3.3 Net radiation and soil heat flux

Application of the BR-DTS method requires the measurement of net radiation and soil heat flux. Net radiation was measured on two locations approximately 10 m apart using a NR-LITE net radiometer (Kipp and Zonen, Delft, The Netherlands). Both were located at 1 m above the ground surface and situated within a 20 m radius of the BR-DTS experimental set up. For the data processing the average of both sensors is used.

The soil heat flux was measured using two soil heat flux plates (HFT-S, REBS, Seattle, WA) which were placed at a depth of 80 mm below the soil surface. One was placed close to the BR-DTS set up in between the crops and the other was placed at the edge of the field under the crops. In addition, a system of parallel thermocouples at depths of 20 and 60 mm were used for measuring the soil heat stored above the soil heat flux plates. The volumetric soil water content in the first 60 mm was measured using a CS615 time domain reflectometer (TDR). This equipment was located 10 m away from the BR-DTS set-up, in between the sugar beet plants. The records of soil moisture were used to determine the soil heat capacity which was central for heat storage calculations. The data from both measuring locations were averaged during the data processing.

4 Results and discussion

The results presented in this section focus on the DTS measurements, as the quality assessment of these measurements is the aim of this paper. First, the meteorological conditions are presented. Second, the results of BR-DTS are compared with the other techniques, followed by a comparison of BR-DTS applying 13 data points and 2 data points to investigate the advantage of using high spatial resolution dry and wet bulb temperature measurements.

HESSD
10, 7161–7196, 2013

4.1 Meteorological conditions

Although the measurement period was short, measurements were performed under different meteorological conditions. There were cloudless sunny days (9 and 16 November), a full day with overcast conditions (10 November) and partly cloudy days (17 and 18 November). Net radiation around noon varied between 100 and 700 $\mathrm{W\,m^{-2}}$. Wind direction varied during all days, but was mainly between south and south-east. Wind speed varied between 0 and 4 $\mathrm{m\,s^{-1}}$ during the measurement period, with wind speed being the highest during the afternoon for most of the days. On all of the considered days wind speed increased around sunrise. The lowest daytime averaged temperature was measured on 10 November and was 16 °C. The highest daytime averaged temperature was measured on 16 November and was 24 °C (see also Fig. 5).

4.2 How well did the BR-DTS perform?

Figure 6 shows the calculated Bowen ratio values for the experimental days, together with the correlation coefficients (R^2) at each 30 min interval derived from determining the Bowen ratio value based on the 13 measurement points (as explained in Sect. 3.1.3 and Fig. 4). High R^2 values indicate a linear relation for temperature and vapour pressure over the air column. High R^2 values can be seen during the day, with occasionally low values, which can be explained by the negative influence of wind direction and wind speed for our set-up (see Figs. 8 and 9).

Figure 7 shows the comparison of latent heat obtained with the BR-DTS and with the reference techniques. The $\mathrm{LE_{SEB}}$, $\mathrm{LE_{SLS}}$ and $\mathrm{LE_{SR}}$ were derived as a residual of the surface energy balance equation. There was very good agreement between the BR-DTS and EC-indirect, SLS and SR latent heat flux estimates (see Table 1). The regression coefficient of BR-DTS with data from all three methods is 0.97 and the slope of the trend line is 0.92 which implies that BR-DTS overestimates the latent heat consistently by 8 %. All three techniques are widely accepted for estimating actual evaporation in South Africa (Clulow et al., 2012; Mengistu and Savage, 2010; Odhiambo and Savage, 2009; Savage, 2009a), and a marginal error of 10 % lies within the uncertainty envelope of these techniques (Twine et al., 2000). Instrumental errors and energy balance closure problems are often incorporated in the measurement records. Hence, it can be concluded that BR-DTS estimates for actual evaporation are credible.

However, the BR-DTS latent heat flux estimates did not compare well with the directly measured latent heat flux using the Infrared gas analyser of the EC technique. This is an indication that this direct measured latent heat flux from the EC technique are less reliable. Fritschen et al. (1992) already showed that the errors in the direct measured latent heat flux determined with an eddy covariance system were often larger than the errors in the sensible heat flux. Teixeira and Bastiaanssen (2010) showed that large corrections of LE_{EC} are required. Therefore we only show results from the EC-indirect method in the remaining analyses.

The latent heat flux estimates presented in Fig. 7 only show the days when wind direction in combination with wind speed did not cause improper measurement conditions. During strong north easterly wind conditions (winds between 350 and 35° and with a wind speed above 0.75 ms^{-1}), the wind blew surplus water from the wet cable onto the dry cable, which was under these conditions located downwind from the wet cable, and affected the measurements. A shelter needs to be developed in the future version of the DTS tower to prevent this process.

Figure 8 shows a comparison of the latent heat flux estimates, from 9 to 18 November, excluding measurements on 9 November and during the night of 10 November, when EC measurements were interrupted and from 11 November 13:00 LT till 14 November 12:00 LT, when DTS measurements were interrupted. From outliers of the regression line it was deduced that improper measurement conditions occurred with winds between 350 and 35° and wind speeds above 0.75 ms^{-1}. The time periods with strong north easterly winds are indicated with open circles (Fig. 8). The relative error $((LE_{BR\text{-}DTS} - LE_{SEB})/LE_{SEB})$ for varying wind speeds also shows the influence of wind speed and direction on increasing the error in the BR-DTS (Fig. 9).

HESSD
10, 7161–7196, 2013

4.3 Comparison of Bowen ratio for 2 and 13 data points

In this section we compare the Bowen ratio values derived from 13 levels (BR-DTS) with the Bowen ratio values derived from 2 levels. In case of two measuring levels, the height of the lower level measurements commonly in the international literature is 0.3 m (Fuchs and Tanner, 1970), 0.0 to 0.6 m (Dugas et al., 1991) and 1.5 m above canopy height (Nagler et al., 2005). Higher levels are typically found at and 1.0 m (Fuchs and Tanner, 1970), 1.0 to 1.6 m (Dugas et al., 1991) and 2.5 m (Nagler et al., 2005). Following this range, we consider 0.5 and 1.5 m above the canopy height for the two data point case. The results are presented in Fig. 10. It should be noted again that this was done on the basis of DTS results, hence only evaluating the advantage of the high resolution vertical temperature profile on the Bowen ratio value.

For the days analysed (day time only and excluding periods of strong north easterly winds) we noticed a stronger temporal variation of the Bowen ratio values based on 2 points (dashed line) compared to Bowen ratio values based on 13 points (continuous line), often at sunset when the Bowen ratio was indeterminate. This was confirmed by comparing the standard deviations of the Bowen ratio values. Daily standard deviations for 2 and 13 data points are shown in Table 2, it can be seen that the standard deviation is on average 14 % lower when using 13 data points, thus resulting in more constant results and less outliers. While the data set is only based on five days of measurement, it clearly shows that the temporal variation of Bowen ratio measurements with the BR-DTS can be significantly improved, which places the estimation of latent heat from Bowen ratio values back on the list of affordable and accurate field measurement techniques.

Figure 10 also shows the relative error of the Bowen ratio values determined with 2 points in relation to the Bowen ratio determined with 13 points ($(\beta_{2\text{pts}} - \beta_{13\text{pts}})/\beta_{13\text{pts}}$). The error is especially high during sunset and sun rise, but also during daytime the error can be incidentally higher. This supports the concept of using more observation points, as is the case with the BR-DTS method, rather than two, to prevent non necessary outliers.

5 Conclusions and recommendations

The main aim of this research was to verify whether the conceptof BR-DTS measurements with a fibre optic cable can measure the energy balance partitioning, and whether it can be an improvement as compared to conventional two level Bowen ratio measurements.

The results presented above are based on a short measuring campaign, so for a more thorough testing of this method, a longer measuring campaign should be performed. However, from these results still some conclusions can be drawn. The comparison with well-established techniques for estimating latent heat flux showed that BR-DTS has a deviation of 4 % with hourly Eddy covariance, 8 % with the surface layer scintillometer (SLS) and 8 % with hourly surface renewal (SR) techniques. This is within the uncertainty envelope related to these existing technologies (Twine et al., 2000), thus the BR-DTS can give acceptable results. In addition the BR-DTS shows very consistent correlation with the three other techniques (correlation coefficients of 0.97 and 0.98), so all techniques give comparable results under different circumstances.

The BR-DTS method is less sensitive for measurement errors as one and the same sensor (the fibre optic cable) is used and, secondly, it showed a less spurious behaviour of the Bowen ratio values, as these can be established on the basis of more than two observation points. Table 3 shows an overview of the main advantages and disadvantages of determining latent heat with BR-DTS.

From the operational point also a number of conclusions can be drawn. Due care should be performed in wetting the cotton wrapped cable in order to obtain the real "wet bulb" temperature and at the same time not influencing the measurements of the dry cable. In our set-up strong north easterly winds exacerbated the influence on the dry cable. The water supply was connected to a high pressure irrigation system. This resulted in a large amount of water being supplied to the wetted cable. Fine tuning of the water flow was difficult to achieve manually, and this needs to be automated in the future. The dry bulb temperature should not be affected by the neighbouring wet cable. Options to achieve this are a larger distance between the dry and wet cable, or by making sure the dry cable is always upwind of the wet cable.

Furthermore, an advantage of the BR method with reliable information of vertical air temperature gradients, is the opportunity to combine this with a wind speed profile. From a vertical wind speed profile the friction velocity $u*$ and consequently the sensible heat H can be derived (Qiu et al., 1998; Brutsaert, 2005). Together with the Bowen ratio, H/LE, this delivers the latent heat LE and bypasses the need to determine the net available energy $R_\mathrm{n} - G$. Alternatively, measurement of the Bowen ratio and u^* becomes a method to determine the net available energy, as $R_\mathrm{n} - G = H + \mathrm{LE}$. Hence, adding simple measurements of u^* will create the opportunity to measure all key components of the surface energy balance.

Having demonstrated that the concept of BR-DTS can work, we see wider applications, for example for determining evaporation under and above the canopy. In addition, BR-DTS can also be used to investigate the spatial distribution of actual evaporation and become a ground measurement to validate remote sensed evaporation.

Prices of laser analysing equipment rapidly decreased over the last years. Hence, the costs of the DTS equipment in the coming years. The fact that nowadays DTS equipment exists with 0.2 m resolution demonstrates the rapid development and interest in the technique. This specific development would no longer require the use of spiralled cables for the BR-DTS technique and would already simplify the experimental setup of the BR-DTS technique.

References

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration – Guidelines for computing crop water requirements, vol. 56, FAO – Food and Agriculture Organization of the United Nations, Rome, 1998. 7166, 7167

Angus, D. E. and Watts, P. J.: Evapotranspiration – How good is the Bowen ratio method?, Agr. Water Manage., 8, 133–150, 1984. 7164, 7166

Aston, A. R.: The effect of vertical separation of psychrometers on the determination of Bowen ratios over a young eucalypt forest, Agr. Forest Meteorol., 35, 299–307, 1985. 7164, 7168

Atta, C. W. V.: Effect of coherent structures on structure functions of temperature in the atmospheric boundary layer, Arch. Mech., 29, 161–171, 1977. 7172

Bastiaanssen, W. G. M., Cheema, M. J. M., Immerzeel, W. W., Miltenburg, I. J., and Pelgrum, H.: Surface energy balance and actual evapotranspiration of the transboundary Indus Basin estimated from satellite measurements and the ETLook model, Water Resour. Res., 48, W11512, doi:10.1029/2011WR0101482, 2012. 7163

Black, T. A. and McNaughton, K. G.: Psychrometric apparatus for Bowen-Ratio determination over forests, Bound.-Lay. Meteorol., 2, 246–254, 2012. 7164

Bowen, I. S.: The ratio of heat losses by conduction and by evaporation from any water surface, Phys. Rev., 27, 779–787, 1926. 7163, 7166

Brutsaert, W.: Hydrology, an intr, Cambridge University Press, New York, 2005. 7178

Burt, C. M., Mutziger, A. J., Allen, R. G., and Howell, T. A.: Evaporation Research: Review and Interpretation, J. Irrig. Drain Eng., 131, 37–58, 2005. 7163

Clulow, A. D., Everson, C. S., Mengistu, M. G., Jarmain, C., Jewitt, G. P. W., Price, J. S., and Grundling, P.-L.: Measurement and modelling of evaporation from a coastal wetland in Maputaland, South Africa, Hydrol. Earth Syst. Sci., 16, 3233–3247, doi:10.5194/hess-16-3233-2012, 2012. 7174

Courault, D., Seguin, B., and Olioso, A.: Review on estimation of evapotranspiration from remote sensing data: From empirical to numerical modeling approaches, Irrig. Drain. Syst., 19, 223–249, doi:10.1007/s10795-005-5186-0, 2005. 7163

Dugas, W. A., Frltschen, L. J., Gay, L. W., Held, A. A., Matthlas, A. D., Relcosky, D. C., Steduto, P., and Stelner, J. L.: Bowen ratio, eddy correlation, and portable chamber measurements of sensible and latent heat flux over irrigated spring wheat, Agr. Forest Meteorol., 56, 1–20, 1991. 7163, 7176

HESSD
10, 7161–7196, 2013

Bowen ratio with DTS

T. Euser et al.

Dyer, A. J. and Hicks, B. B.: Flux-gradient relationships in the constant flux layer, Q. J. Roy. Meteorol. Soc., 96, 715–721, doi:10.1002/qj.49709641012, 1970. 7166
Fritschen, L. J.: Accuracy of evapotranspiration determinations by the Bowen ratio method, IAHS Bull., 10, 38–48, 1965. 7168
Fritschen, L. J. and Qian, P.: Net radiation, sensible and latent heat flux densities on slopes computed by the energy balance method, Bound.-Lay. Meteorol., 53, 163–171, 1990. 7164
Fritschen, L. J. and Simpson, J. R.: Surface energy balance and radiation systems: general description and improvements, J. Appl. Meteorol., 28, 680–689, 1989. 7166
Fritschen, L. J., Qian, P., Kanemasu, E. T., Nie, D., Smith, E. A., Stewart, J. B., Verma, S. B., and Wesely, M. L.: Comparisons of Surface Flux Measurement Systems Used in FIFE 1989, J. Geophys. Res., 97, 18697–18713, 1992. 7175
Fuchs, M. and Tanner, C. B.: Error analysis of bowen ratios measured by differential psychrometry, Agr. Meteorol., 7, 329–334, 1970. 7164, 7176
Gavilán, P. and Berengena, J.: Accuracy of the Bowen ratio-energy balance method for measuring latent heat flux in a semiarid advective environment, Irrig. Sci., 25, 127–140, 2007. 7166
Hoes, O. A. C., Schilperoort, R. P. S., Luxemburg, W. M. J., Clemens, F. H. L. R., and van de Giesen, N. C.: Locating illicit connections in storm water sewers using fiber-optic distributed temperature sensing, Water Res., 43, 5187–5197, 2009. 7164
Jara, J., Stockle, C. O., and Kjelgaard, J.: Measurement of evapotranspiration and its components in a corn (Zea Mays L.) field, Agr. Forest Meteorol., 92, 131–145, 1998. 7164
Kalma, J. D., McVicar, T. R., and McCabe, M. F.: Estimating Land Surface Evaporation: A Review of Methods Using Remotely Sensed Surface Temperature Data, Surv. Geophys., 29, 421–469, 2008. 7163
Krzeminska, D. M., Steele-Dunne, S. C., Bogaard, T. A., Rutten, M. M., Sailhac, P., and Geraud, Y.: High-resolution temperature observations to monitor soil thermal properties as a proxy for soil moisture condition in clay-shale landslide, Hydrol. Process., 26, 2143–2156, 2011. 7164
Maidment, D. R.: Handbook of Hydrology, McGraw-Hill, Inc., 1993. 7166
Malek, E. and Bingham, G. E.: Comparison of the Bowen ratio-energy balance and the water balance methods for the measurement of evapotranspiration, J. Hydrol., 146, 209–220, 1993. 7163

HESSD
10, 7161–7196, 2013
Bowen ratio with DTS
T. Euser et al.

Mauder, M., Cuntz, M., Drüe, C., Graf, A., Rebmann, C., Schmid, H. P., Schmidt, M., and Steinbrecher, R.: A strategy for quality and uncertainty assessment of long-term eddy-covariance measurements, Agr. Forest Meteorol., 169, 122–135, 2013. 7163
Meijninger, W. M. L. and de Bruin, H. A. R.: The sensible heat fluxes over irrigated areas in western Turkey determined with a large aperture scintillometer, J. Hydrol., 229, 42–49, 2000. 7165
Mengistu, M. G. and Savage, M. J.: Open water evaporation estimation for a small shallow reservoir in winter using surface renewal, J. Hydrol., 380, 27–35, 2010. 7174
Nagler, P. L., Scott, R. L., Westenburg, C., Cleverly, J. R., Glenn, E. P., and Huete, A. R.: Evapotranspiration on western U.S. rivers estimated using the Enhanced Vegetation Index from MODIS and data from eddy covariance and Bowen ratio flux towers, Remote Sens. Environ., 97, 337–351, 2005. 7176
Odhiambo, G. O. and Savage, M. J.: Sensible Heat Flux by Surface Layer Scintillometry and Eddy Covariance over a Mixed Grassland Community as Affected by Bowen ratio and MOST Formulations for Unstable Conditions, J. Hydrometeorol., 10, 479–492, 2009. 7174
Peacock, C. E. and Hess, T. M.: Estimating evapotranspiration from a reed bed using the Bowen ratio energy balance method, Hydrol. Process., 18, 247–260, 2004. 7164
Perez, P. J., Castellvi, F., Ibañez, M., and Rosell, J. I.: Assessment of reliability of Bowen ratio method for partitioning fluxes, Agr. Forest Meteorol., 97, 141–150, 1999. 7164, 7168
Perry, C. J.: Efficient irrigation; inefficient communication; flawed recommendations, Irrig. Drain., 56, 367–378, 2007. 7162
Qiu, G. Y., Yano, T., and Momii, K.: An improved methodology to measure evaporation from bare soil based on comparison of surface temperature with a dry soil surface, J. Hydrol., 210, 93–105, 1998. 7178
Rana, G. and Katerjib, N.: Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: a review, Eur. J. Agron., 13, 125–153, 2000. 7163
Savage, M. J.: Estimation of evaporation using a dual-beam surface layer scintillometer and component energy balance measurements, Agr. Forest Meteorol., 149, 501–517, 2009a. 7175
Savage, M. J., Everson, C. S., and Metelerkamp, B. R.: Evaporation measurement above vegetated surfaces using micrometeorological techniques, vol. WRC Report No. 349/1/97, WRC – South African Water Research Commission, 1997. 7164

Savage, M. J., Everson, C. S., and Metelerkamp, B. R.: Bowen ratio evaporation measurement in a remote montane grassland: Data integrity and fluxes, J. Hydrol., 376, 249–260, 2009b. 7164

Schoups, G., van de Giesen, N. C., and Savenije, H. H. G.: Model complexity control for hydrologic prediction, Water Resour. Res., 44, W00B03, doi:10.1029/2008WR006836, 2008. 7163

Selker, J. S., Venaz, L. T., Huwald, H., Mallet, A., Luxemburg, W., v. d. Giesen, N., Stejskal, M., Zeman, J., Westhoff, M., and Parlange, M. B.: Distributed fiber-optic temperature sensing for hydrologic systems, Water Resour. Res., 42, W12202, doi:10.1029/2006WR005326, 2006. 7164, 7168, 7169

Sellers, P. J., Mintz, Y., Sud, Y. C., and Dalcher, A.: A Simple Biosphere Model (SIB) for Use within General Circulation Models, J. Atmos. Sci., 43, 505–531, 1986. 7163

Sen: ORYX DTS – Data sheet, Sensornet, http://www.sensornet.co.uk/technology/distributed-temperature-sensing/oryx-dts/ (last access: 12 December 2011), 2009. 7168

Spittlehouse, D. L. and Black, T. A.: Evaluation of the Bowen ratio/energy balance method for determining forest evapotranspiration, Atmos. Ocean, 18, 98–116, 1980. 7166

Steele-Dunne, S. C., Rutten, M. M., Krzeminska, D. M., Hausner, M., Tyler, S. W., Selker, J., Bogaard, T. A., and van de Giesen, N. C.: Feasibility of soil moisture estimation using passive distributed temperature sensing, Water Resour. Res., 46, W03534, doi:10.1029/2009WR008272, 2010. 7164

Teixeira, A. H. C. and Bastiaanssen, W. G. M.: Five methods to interpret field measurements of energy fluxes over a micro-sprinkler-irrigated mango orchard, Irrig. Sci., 30, 13–28, doi:10.1007/s00271-010-0256-y, 2010. 7163, 7175

Teixeira, A. H. C., de Castro, A. H., Bastiaanssen, W. G. M., and Bassoi, L. H.: Crop water parameters of irrigated wine and table grapes to support water productivity analysis in the Sao Francisco river basin, Brazil. Agr. Water Manage., 94, 31–42, 2007. 7164

Todd, R. W., Evett, S. R., and Howell, T. A.: The Bowen ratio-energy balance method for estimating latent heat flux of irrigated alfalfa evaluated in a semi-arid, advective environment, Agr. Forest Meteorol., 103, 335–348, 2000. 7166

Twine, T. E., Kustas, W. P., Norman, J. M., Cook, D. R., Houser, P. R., Meyers, T. P., Prueger, J. H., Starks, P. J., and Wesely, M. L.: Correcting eddy-covariance flux underestimates over a grassland, Agr. Forest Meteorol., 103, 279–300, 2000. 7175, 7177

Tyler, S. W., Selker, J. S., Hausner, M. B., Hatch, C. E., Torgersen, T., Thodal, C. E., and Schladow, S. G.: Environmental temperature sensing using Raman spectra DTS fiber-optic methods, Water Resour. Res., 45, W00D23, doi:10.1029/2008WR007052, 2009. 7164, 7168

Uhlenbrook, S., Roser, S., and Tilch, N.: Hydrological process representation at the meso-scale: the potential of a distributed, conceptual catchment model, J. Hydrol., 291, 278–296, 2004. 7163

Westhoff, M. C., Bogaard, T. A., and Savenije, H. H. G.: Quantifying the effect of in-stream rock clasts on the retardation of heat along a stream, Adv. Water Res., 33, 1417–1425, 2010. 7164

Winsemius, H. C., Savenije, H. H. G., and Bastiaanssen, W. G. M.: Constraining model parameters on remotely sensed evaporation: justification for distribution in ungauged basins?, Hydrol. Earth Syst. Sci., 12, 1403–1413, doi:10.5194/hess-12-1403-2008, 2008. 7163

Wipfler, E. L., Metselaar, K., van Dam, J. C., Feddes, R. A., van Meijgaard, E., van Ulft, L. H., van den Hurk, B., Zwart, S. J., and Bastiaanssen, W. G. M.: Seasonal evaluation of the land surface scheme HTESSEL against remote sensing derived energy fluxes of the Transdanubian region in Hungary, Hydrol. Earth Syst. Sci., 15, 1257–1271, doi:10.5194/hess-15-1257-2011, 2011. 7163

Xing, Z., Chow, L., Meng, F. R., Rees, H. W., Stevens, L., and Monteith, J.: Validating Evapotranspiraiton Equations Using Bowen Ratio in New Brunswick, Maritime, Canada, Sensors, 8, 412–428, 2008. 7163

HESSD
10, 7161–7196, 2013

Bowen ratio with DTS

T. Euser et al.

Table 1. Results of the regression analysis for all methods separately and for the combination of EC-indirect, SLS and SR (combined). Data used from 9, 10, 17, 18 November. The linear regression is forced through (0, 0).

	Slope linear regression (–)	R^2 of linear regression (–)
EC_{direct}	0.37	0.15
EC	0.96	0.98
SLS	0.92	0.96
SR	0.92	0.97
Combined	0.92	0.97

HESSD
10, 7161–7196, 2013

Table 2. Standard deviation of Bowen ratio values based on two points and Bowen ratio values based on 13 points. The last column shows the decrease in standard deviation between the two. A decrease in standard deviation means less spurious results.

Date	Std deviation 2 pts	Std deviation 13 pts	Improvement
9 November	0.23	0.22	4 %
10 November	0.28	0.26	8 %
16 November	0.24	0.21	10 %
17 November	0.15	0.09	37 %
18 November	0.09	0.06	29 %
Averaged	0.20	0.17	14 %

HESSD
10, 7161–7196, 2013

Table 3. Overview of the main advantages and disadvantages of determining latent heat with BR-DTS.

Advantages	Disadvantages
Closure of the energy budget guaranteed	The water supply needs to be refined, and methods for that need to be developed
Cheap methodology, especially in the near future when prizes are expected to decrease for the equipment	By absence of a shelter, the wet cable affects the dry cable if certain upwind directions prevail
Data is simple to interpret	The latent heat is slightly overestimated (8%), although this is a soft comparison
Potential opportunity to measure soil evaporation and canopy evaporation separately	A sufficient fetch is required for good measurement results
Potential to map absolute fluxes of sensible and latent heat if friction velocity (u_*) can be estimated with an accurate method	

HESSD
10, 7161–7196, 2013

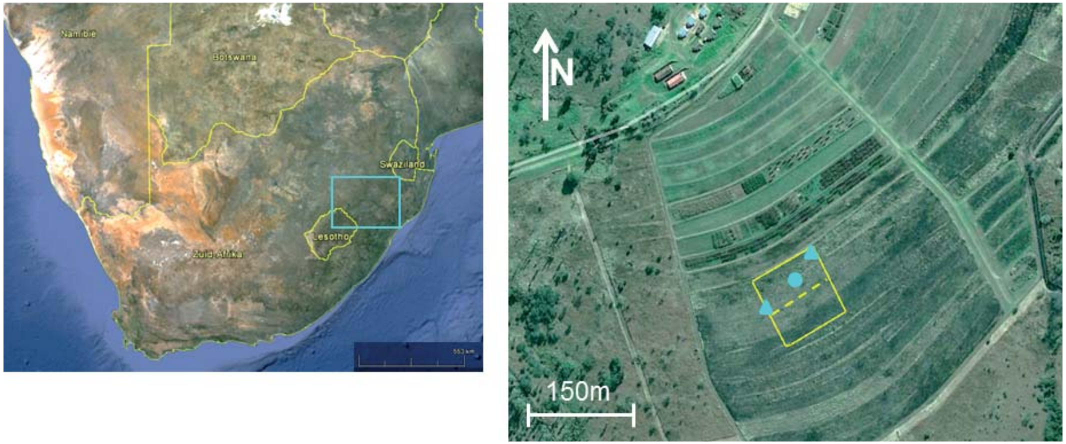

Fig. 1. Location of the Ukulinga research farm. The blue dot indicates the location of the experimental setup for the BR-DTS, EC and SR measurement systems. The blue triangles indicate the position of the transmitter and receiver of the SLS.

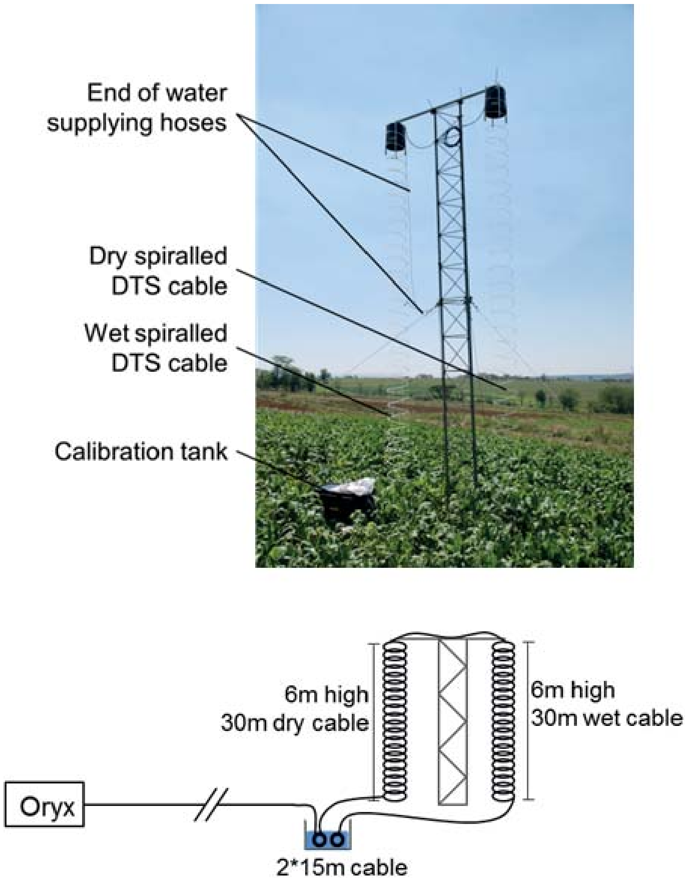

Fig. 2. Experimental setup for BR-DTS at Ukulinga Research Farm. Top panel: picture of setup in the field. Bottom panel: schematic overview of the setup.

HESSD
10, 7161–7196, 2013

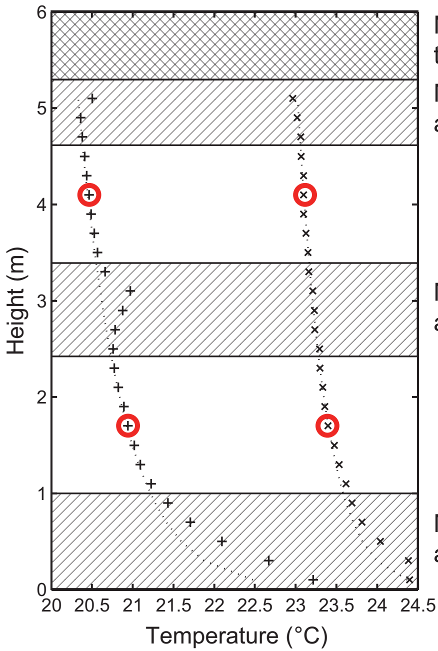

Fig. 3. Temperature profiles for 17 November 2012 at 12:00 h (for the period 11:45–12:15 LT). The grey bars indicate excluded data points ("+" = wet cable, "x" = dry cable). The dotted line shows a logarithmic profile, which is fitted to the data points indicated with a red circle.

HESSD
10, 7161–7196, 2013

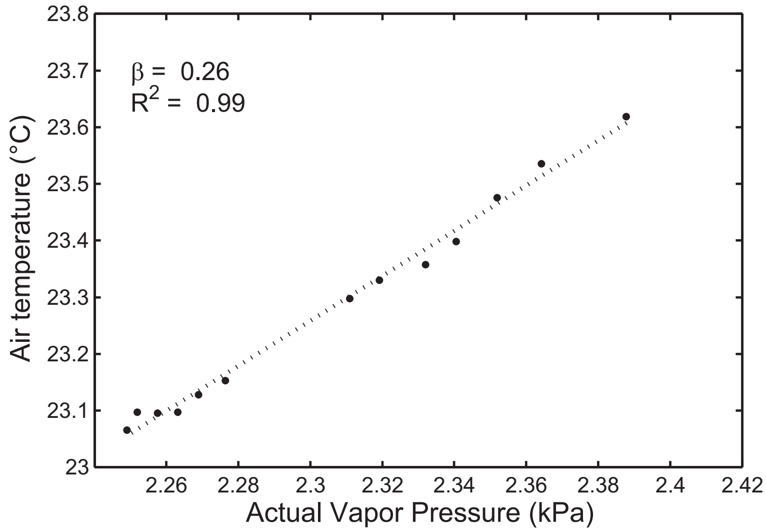

Fig. 4. Example of calculation of a Bowen ratio: each dot represents a measurement in the vertical for 17 November 2011 at 12:00 h (for the period 11:45–12:15 LT); only the data points derived in Fig. 3 are used in this figure. The Bowen ratio was calculated by multiplying the slope of the trend line by the psychrometric constant (0.059 kPa °C^{-1}), as described by Eq. (1).

HESSD
10, 7161–7196, 2013

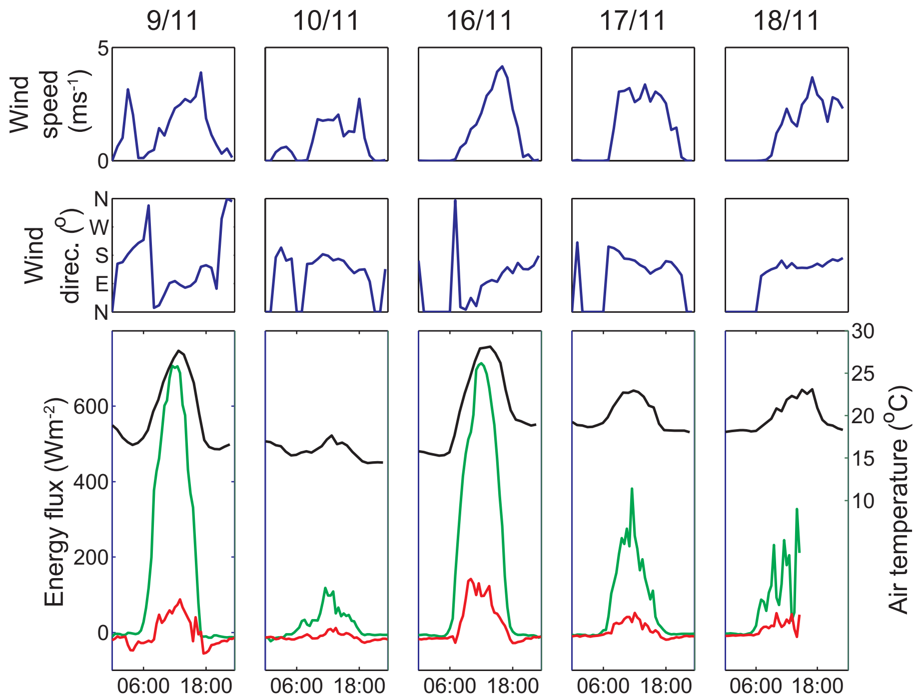

Fig. 5. Meteorological conditions and energy fluxes for the days used in the data analysis. Top panel: wind speed, middle panel: wind direction, bottom panel: net radiation, soil heat flux and air temperature at 2 m height (green = net radiation, red = soil heat flux, black = temperature).

HESSD
10, 7161–7196, 2013

Bowen ratio with DTS

T. Euser et al.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀▌ ▐▶
◀ ▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

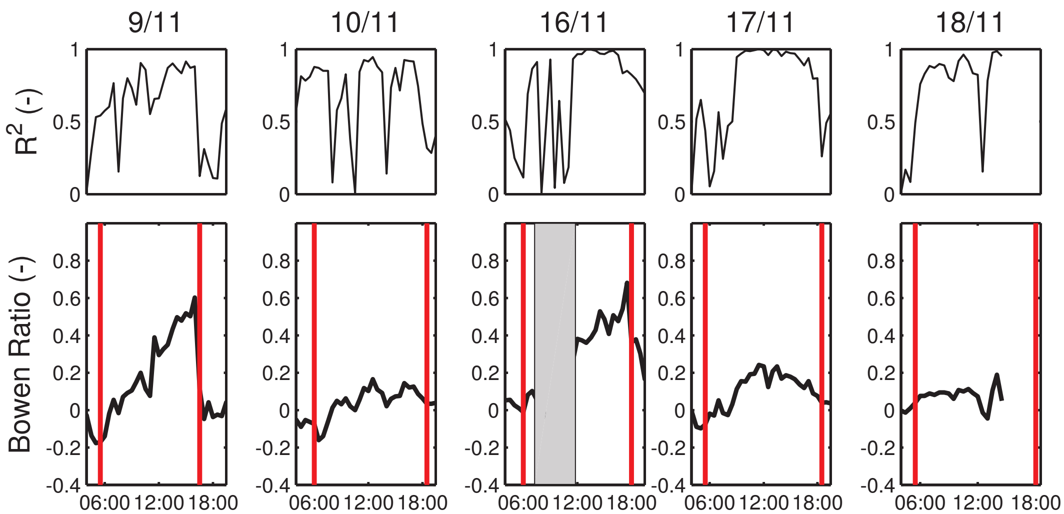

Fig. 6. Top panel: R^2 value for calculating the Bowen ratio from 13 data points of T_a and e_a between 1 and 4.6 m (Fig. 4). Bottom panel: half hourly Bowen ratio values for the 13 data points. The vertical red lines show the moments of sun rise and sun set, the grey bar on 16 November shows a period with strong north easterly winds.

HESSD
10, 7161–7196, 2013

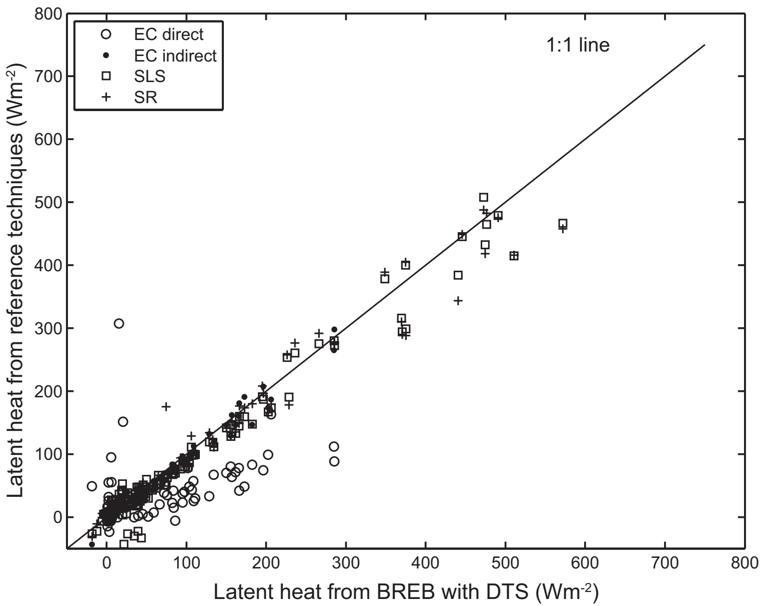

Fig. 7. Comparison of the half hourly latent heat flux estimates of BR-DTS with reference techniques. Data used from 9, 10, 17 and 18 November, both day and night time values are presented.

HESSD
10, 7161–7196, 2013

Bowen ratio with DTS

T. Euser et al.

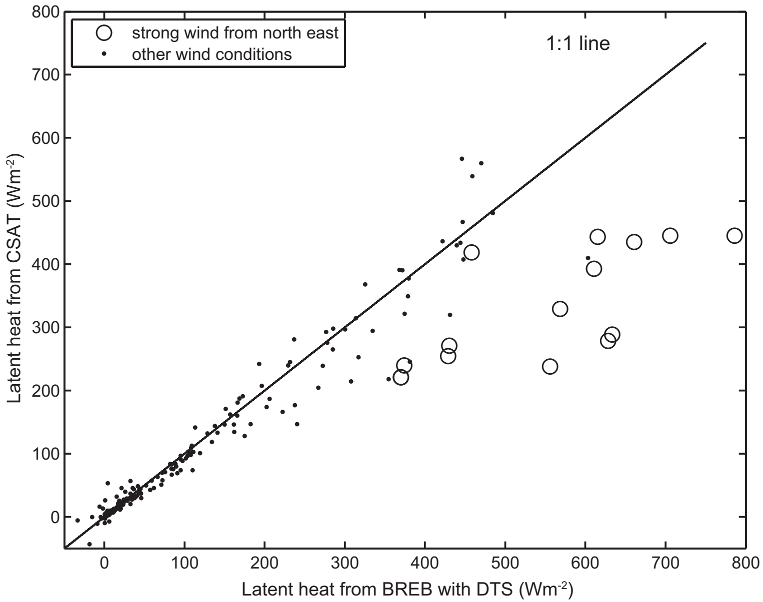

Fig. 8. Comparison of the latent heat flux of BR-DTS with latent heat flux estimates from the Eddy Covariance (EC_{SEB}) from 9 to 18 November.

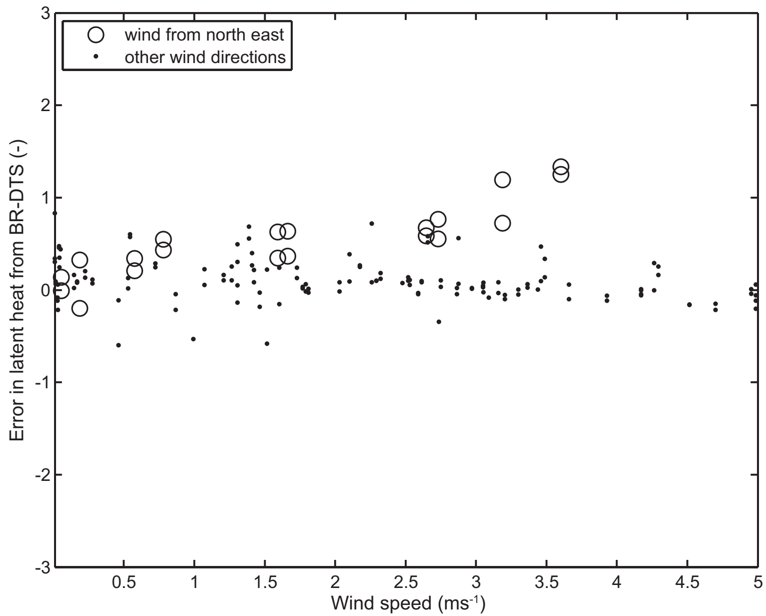

Fig. 9. The relative error of the latent heat from BR-DTS in respect to LE_{SEB} for varying wind speed. Values for a measured wind speed of $0\,ms^{-1}$ are not shown, as the direction cannot be determined.

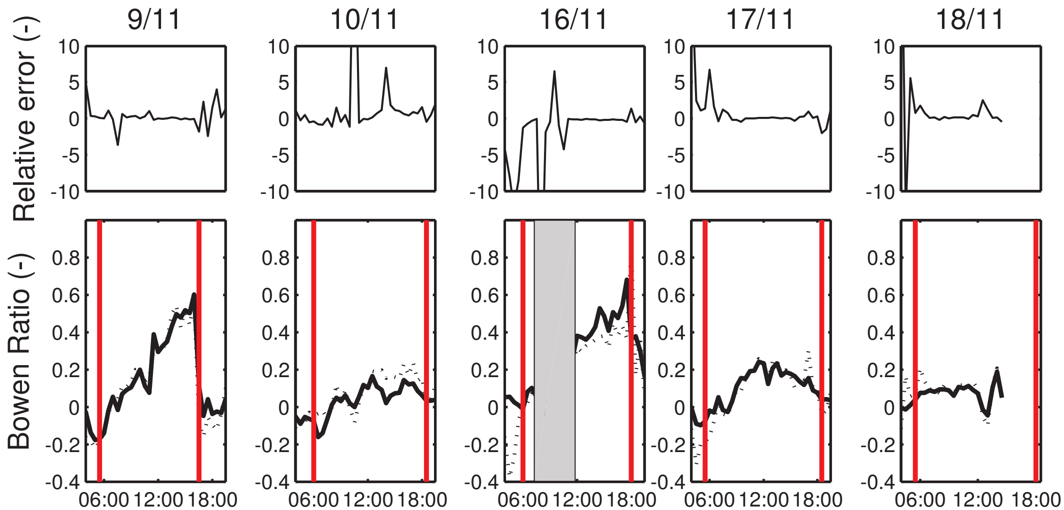

Fig. 10. Top panel: relative error of the Bowen ratio determined with 2 data points in relation to the Bowen ratio determined with 13 points $((\beta_{2pts} - \beta_{13pts})/\beta_{13pts})$ Bottom panel: Bowen ratio values, the solid line shows the Bowen ratio for the 13 data points between 1 and 4.6 m; the dotted line shows the Bowen ratio for only two measuring points (at 1 and 2 m above the ground). The vertical red lines show the moments of sun rise and sun set, the grey bar on 16 November shows a period with strong north easterly winds.

HESSD
10, 7161–7196, 2013

Bowen ratio with DTS

T. Euser et al.